

**Holocene Sedimentary Environments of the Goat Meadows
Watershed, Southern Coast Mountains, British Columbia**
**Les environnements sédimentaires à l'Holocène dans le bassin
versant de Great Meadows, dans le sud de la chaîne Côtière,
Colombie-Britannique**
**Sediment-Umwelt im Holozän im Great-Meadows
Einzugsgebiet, südliche Küstenberge, British Columbia**

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Résumé de l'article

On présente ici les résultats d'une étude sur l'érosion et la sédimentation à l'Holocène dans un petit bassin versant subalpin du sud de la chaîne Côtière fondée sur les sédiments lacustres. L'étude portait sur la détermination du volume et de la masse de sédiments accumulés au cours de chacune des quatre périodes étudiées (10 510-6700 BP; 6700-6340 BP; 6340-2400 BP; 2400 BP à aujourd'hui), l'analyse des propriétés physiques, chimiques et minéralogiques des sédiments et l'interprétation des paléoenvironnements selon les taux d'érosion et de sédimentation, de la provenance des sédiments et de la productivité organique. Tout indique que la période paraglaciale a pris fin vers 10 000 BP et qu'elle a été suivie d'une période caractérisée par une faible sédimentation (10 000-6700 BP). Les taux élevés de sédimentation obtenus pour la période de 6700 à 6340 BP reflètent peut-être l'existence de taux d'érosion accélérés au cours de l'intervalle xéothermique, plus chaud et plus sec. De 6300 à 2400 BP, les taux ont de nouveau diminué pour remonter de nouveau au cours de la période la plus récente (après 2400 BP). On formule l'hypothèse que des conditions climatiques progressivement plus froides et plus humides ont contribué à réactiver les matériaux déjà altérés sur les versants. L'analyse des sédiments sur les versants appuie cette hypothèse.

HOLOCENE SEDIMENTARY ENVIRONMENTS OF THE GOAT MEADOWS WATERSHED, SOUTHERN COAST MOUNTAINS, BRITISH COLUMBIA

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ABSTRACT This paper presents the results of an investigation of Holocene erosion and sedimentation in a small subalpine watershed in the southern Coast Mountains of British Columbia. The study involved determinations of the volume and mass of lake sediments accumulated during each of four time periods (10,510-6700 BP; 6700-6340 BP; 6340-2400 BP; and, 2400 BP to the present); analysis of physical, chemical and mineralogical properties of the sediments and palaeoenvironmental interpretations of erosion and sedimentation rates, sediment sources and organic productivity. Indications are that the paraglacial period was complete by ca. 10,000 BP and that there followed a period of low sedimentation (10,000-6700 BP); higher sedimentation rates determined for the period 6700-6340 BP may reflect accelerated rates of erosion during the warmer/drier xerothermic interval. Rates declined again during the period 6340-2400 to be followed by higher rates in the most recent period (post 2400 BP). It is hypothesised that progressively cooler and wetter conditions have activated the older weathered slope materials. Analysis of slope sediments is consistent with this hypothesis.

RÉSUMÉ *Les environnements sédimentaires à l'Holocène dans le bassin versant de Great Meadows, dans le sud de la chaîne Côtière, Colombie-Britannique.* On présente ici les résultats d'une étude sur l'érosion et la sédimentation à l'Holocène dans un petit bassin versant subalpin du sud de la chaîne Côtière fondée sur les sédiments lacustres. L'étude portait sur la détermination du volume et de la masse de sédiments accumulés au cours de chacune des quatre périodes étudiées (10 510-6700 BP; 6700-6340 BP; 6340-2400 BP; 2400 BP à aujourd'hui), l'analyse des propriétés physiques, chimiques et minéralogiques des sédiments et l'interprétation des paléoenvironnements selon les taux d'érosion et de sédimentation, de la provenance des sédiments et de la productivité organique. Tout indique que la période paraglaciale a pris fin vers 10 000 BP et qu'elle a été suivie d'une période caractérisée par une faible sédimentation (10 000-6700 BP). Les taux élevés de sédimentation obtenus pour la période de 6700 à 6340 BP reflètent peut-être l'existence de taux d'érosion accélérés au cours de l'intervalle xéothermique, plus chaud et plus sec. De 6300 à 2400 BP, les taux ont de nouveau diminué pour remonter de nouveau au cours de la période la plus récente (après 2400 BP). On formule l'hypothèse que des conditions climatiques progressivement plus froides et plus humides ont contribué à réactiver les matériaux déjà altérés sur les versants. L'analyse des sédiments sur les versants appuie cette hypothèse.

ZUSAMMENFASSUNG *Sediment-Umwelt im Holozän im Great-Meadows Einzugsgebiet, südliche Küstenberge, British Columbia.* In dieser Studie werden die Ergebnisse einer Untersuchung der Erosion und Sedimentierung im Holozän in einem kleinen subalpinen Einzugsgebiet in den südlichen Küstenbergen von British Columbia dargestellt. Die Studie umfasste die Bestimmung von Volumen und Masse der Seesedimente, die in jeder der vier untersuchten Zeitabschnitte abgelagert wurden (10,510-6700 v.u.Z., 6700-6340 v.u.Z., 6340-2400 v.u.Z. bis zur Gegenwart), die Analyse der physikalischen, chemischen und mineralogischen Eigenschaften der Sedimente und die Interpretation der Paläoumgebungen aufgrund der Erosions- und Sedimentierungsrate, der Herkunft der Sedimente und organischen Produktivität. Alles weist darauf hin, dass die paraglaziale Periode um etwa 10.000 v.u.Z. beendet war und auf sie eine Periode geringer Sedimentierung folgte (10.000-6700 v.u.Z.); stärkere Sedimentierungsraten, die für die Periode von 6700-6340 v.u.Z. gefunden wurden, spiegeln wohl schnellere Erosionsraten während dem wärmeren/trockeneren xerothermischen Intervall. Die Raten nahmen wieder während der Periode 6340-2400 ab, um dann wieder in der jüngsten Periode (nach 2400 v.u.Z.) zuzunehmen. Die Hypothese wird formuliert, dass zunehmend kühlere und feuchtere klimatische Bedingungen das ältere verwitterte Material auf den Abhängen aktiviert haben. Die Analyse der Sedimente an den Abhängen stützt diese Hypothese.

INTRODUCTION

Patterns of postglacial sedimentation and erosion in the Coast Mountains of British Columbia have been little studied. Investigations undertaken have been concerned primarily with lowland environments and the mountain front-glaciated valley interface, with attention directed to alluvial fans and colluvial apron deposits (Ryder, 1971; Church and Ryder, 1972; Fulton, 1971; Clague, 1986). Over the postglacial period, localised sediment remobilisation influenced the detailed geomorphology of many small alpine and subalpine watersheds, yet little is known of the chronology and importance of such events. The most comprehensive records of long term geomorphic history are found in sediments "stored" in depositional environments. Souch and Slaymaker (1986) proposed a methodology for investigating the sedimentary history of such environments using sediment accumulations in small ponds. This paper presents the results of such a pond-sediment based investigation of Holocene events in a small subalpine drainage basin, the Goat Meadows watershed, in the Coast Mountains of south-western British Columbia (Fig. 1). The major objective of the study was to determine the sedimentary response to climate change of a small unglacierized alpine watershed.

REGIONAL CONTEXT

Previous studies have concluded that throughout British Columbia deglaciation was followed by a period during which erosional and depositional processes were controlled primarily by the susceptibility of glacial drift to redistribution under non-glacial conditions. This interval, in which rapid nonglacial sedimentation was directly conditioned by glaciation, has been termed the paraglacial period (Church and Ryder, 1972).

As slopes stabilised and vegetation became established sediment supply to rivers and streams decreased. This, in conjunction with regional effects of isostatic tilting on river gradients, led to a transition from rapid sediment supply, to gradual reworking and removal of the deposits. Throughout the southern interior of British Columbia Mazama tephra, deposited 6700 yr BP (Porter, 1980), occurs close to the present land surface within talus cones and other colluvial deposits, indicating that mass wasting processes, in general, were most effective in early postglacial time, and that there has been little subsequent remobilisation of material.

Palaeobotanical studies of the Pacific coast of Canada and northwest United States (Heusser *et al.*, 1980; Mathewes and Heusser, 1981; Heusser *et al.*, 1985; Mathewes, 1985), based on both qualitative and numerical reconstructions using transfer functions, indicate generally cool and moist conditions for the period 12,000 to 10,500 yr BP, followed by a rapid climatic amelioration between 10,500 and 10,000 yr BP. A warmer drier period than present is inferred for many sites on the coast prior to about 6500 yr BP. Periods of reduced temperature and/or increased precipitation in the middle and late Holocene Epoch caused the expansion of mountain glaciers and the onset of Neoglacial conditions. These fluctuations occurred irregularly but can be grouped into three main Neoglacial intervals: 6000-5000 yr B.P.; 3300-1900 yr BP; and

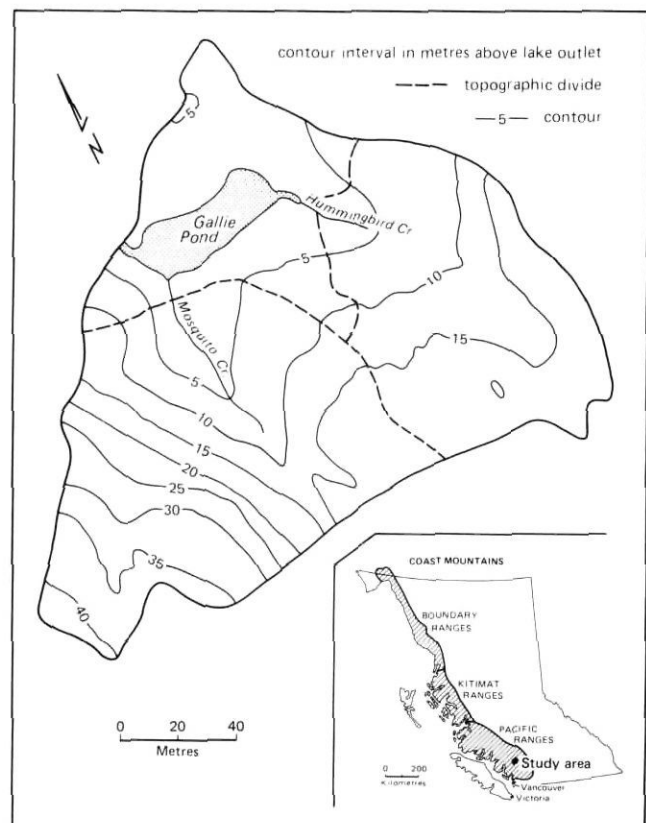


FIGURE 1. Location of the Goat Meadows watershed. Inset map of British Columbia shows Coast Mountains (hatched).

Carte de localisation du bassin versant de Goat Meadows, au sud de la chaîne Côtière, en Colombie-Britannique.

from before 900 yr BP to the present (Ryder and Thompson, 1986). Most glaciers in the wider region have reached their maximum postglacial extent within the last two centuries (Mathews, 1951; Ryder and Thompson, 1986). Cooler, wetter intervals may have led to increased fluvial erosion and sediment transport or the renewal of moisture-dependent forms of mass movement (Ryder, 1978; Bovis, 1985).

STUDY AREA

The Goat Meadows watershed is a 0.024 km² first order catchment which drains into Gallie Pond (unofficial name, Barrett, 1981). Located approximately 120 km north of Vancouver, British Columbia (centred on lat. 50° 24' N, long. 123° 57' W; NTS sheet 92J/7), it lies between 1800 and 1900 m above sea level in the Pacific Ranges of the Coast Mountains (Fig. 1).

The study area lies within the alpine/subalpine ecotone, approximately 50 m above the present forest line. Glaciers in the area are found to elevations of 1500 m above sea level, but intervening ridges, such as the one on which the Goat Meadows watershed is located, have remained ice-free for at least the last 10,500 yr. The contemporary geomorphology of the watershed is dominated by nivation processes, gelifluction and slope wash. Local bedrock consists of metase-

iments of the Late Cretaceous Gambier group (Woodsworth, 1977) and quartz diorite which belongs to the Coast Plutonic Complex (Roddick, 1976). Quartz-actinolite-chlorite-schist underlies 70% of the basin (Gallie, 1983). Bedrock is discontinuously covered by a stony dioritic till, overlain by several fine-textured Holocene deposits. These include two tephra layers, of which the lower is Mazama and the upper is Bridge River. Variable amounts (0.1-0.3 m) of fine textured, organic rich loess deposits are interlayered. Bedrock weathering from groundwater circulation is quantitatively important (Gallie and Slaymaker, 1985). Cryoturbation is inhibited by thick winter snow packs.

Gallie Pond is a small oligotrophic lake fed by two streams (Fig. 2). It is formed in a bedrock depression covered by a well-consolidated deposit believed to be till. Water losses, as indicated by water balance studies (Gallie, 1983), occur through an ephemeral outlet stream at the northwest margin of the pond and by groundwater drainage through the pond sediments and bedrock. The morphometry of Gallie Pond is described in Table I. The pond can be subdivided into two environments: a deeper central portion underlain by fine lacustrine silts; and a peripheral "till shelf", covered by a lag deposit of coarse boulders (Fig. 2). The lake is confined at its outlet by a rock sill which has prevented scouring and erosion of its sediments. The inflow to volume ratio of Gallie Pond is small. According to Brune's (1953) criteria, trap efficiency is in excess of 90%.

Chronological control for sedimentary stratigraphy is provided by two radiocarbon dates, obtained for a separate palynological study by G. E. Rouse, R. M. Bustin and W. H. Mathews, and identification of Mazama and Bridge River tephra. A date of $10,510 \pm 500$ yr BP (WAT-670) was obtained overlying the till, and another of 6340 ± 150 yr BP (I-11471) comes from the top of the peaty deposit (Fig. 3). Mazama tephra deposition occurred 6700 yr BP (Porter, 1980) and Bridge River tephra 2400 yr BP (Mathewes and Westgate, 1980).

METHODS

SAMPLING PROCEDURE

To obtain a representative coverage of the sedimentary environments in Gallie Pond, sampling sites were selected using a 2 x 2 m grid (Souch and Slaymaker, 1986). Twenty six cores were collected (Fig. 2), ranging in length from 0.22 to 0.56 m. All but three of the cores penetrated into the till underlying the lake sediments.

To sample the hillslope surficial sediments of the watershed, the catchment was stratified according to the soil-vegetation units identified by Gallie and Slaymaker (1984). Samples were collected on six transects orthogonal to Gallie Pond. Duplicate pits were dug and horizons sampled in each of the units.

ANALYSES

All the cores were described in terms of the lithostratigraphic units present, texture and colour. Using the criterion of representativeness of all stratigraphic units present, core F1 was

selected as a "master core" on which all analyses were conducted, and with which all other cores were cross-correlated. Material in the Mazama and Bridge River tephra horizons was supplemented from cores E1 and E2.

Each stratigraphic unit was sampled for the determination of minerogenic bulk density (mass clastic sediment per unit volume) and organic matter content (loss on ignition) according to methods outlined by Hillel (1971) and Lavkulich (1981). Textural characteristics of 46 samples were determined using dry sieving techniques and a SediGraph 5000 analyser (Stein, 1985). To assess the sources of sediment, X-ray diffraction of the nine stratigraphic units of the master core, F1, was conducted, and data on the mineralogy of the soils compiled. Relative abundance was inferred from peak heights under

TABLE I

Morphometric characteristics of Gallie Pond; the data refer to the (minimum outlet floor) level of the lake that sustains flow over the outlet rock sill

Gallie Pond	
Site	50°24'N 123°57'W
Altitude (approx.)	1850 m a.s.l.
Maximum length	54 m
Maximum width	21 m
Maximum water depth	1.26 m
Mean water depth	0.61 m
Water volume	481 m ³

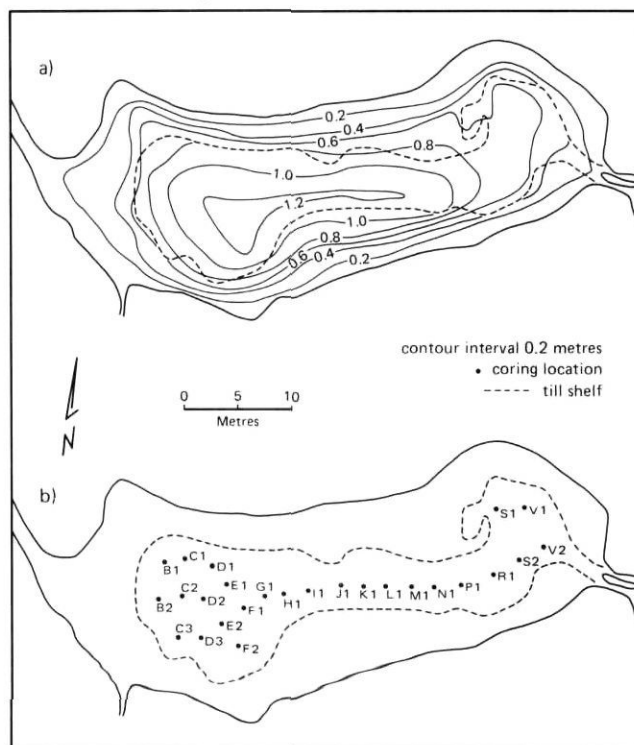


FIGURE 2. Bathymetry of Gallie Pond and coring locations.
Bathymétrie du Gallie Pond et emplacements des sites de carottage.

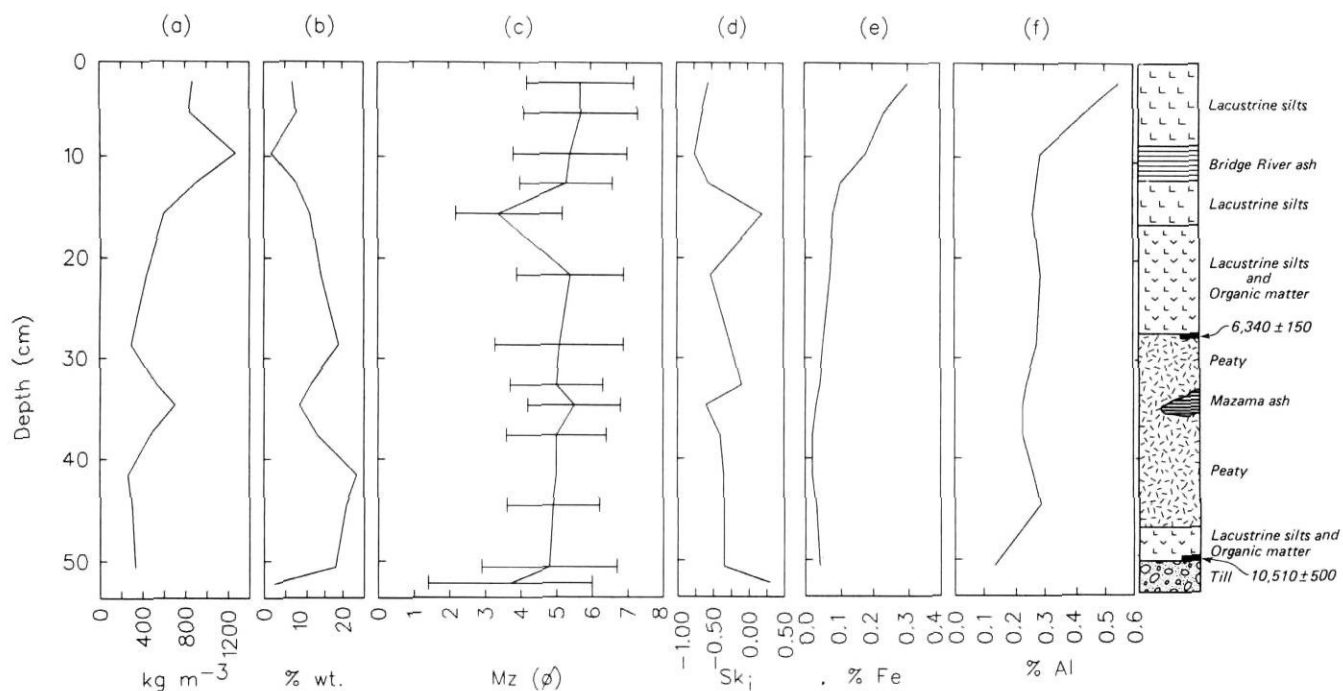


FIGURE 3. Stratigraphy of the master core, F1, with profiles of: a) minerogenic bulk density; b) organic matter content; c) mean grain size with sorting (standard deviation $\pm 2\sigma$); d) skewness; e) % extractable Fe; f) % extractable Al.

Stratigraphie de la carotte principale, n° F1, ainsi que les profils suivants: a) densité apparente d'origine minérale b) teneur en matière organique; c) granulométrie moyenne et triage (écart type de $\pm 2\sigma$); d) asymétrie; e) % de Fe extractible; f) % de Al extractible.

different treatments. In addition, dithionite extractable Fe and Al were determined for core F1 as an index of the relative weathering of the sediments (Birkeland *et al.*, 1979; Arduino *et al.*, 1984). Duplicates were run in all cases to determine the lab errors. These are noted where appropriate.

RESULTS

STRATIGRAPHY OF THE LAKE SEDIMENTS

The stratigraphy of deposits in Gallie Pond provides a continuous record of changes in sedimentation and palaeoenvironments. This is indicated by the undisturbed nature of the deposits, most notably by the Bridge River tephra, which is continuous throughout the lake, displaying sharp contacts with adjacent stratigraphic units, which indicate little mixing or post-depositional redistribution of the tephra.

All the cores exhibit sharp and significant changes in their depositional records, the major features of which are the alternations between peaty material, highly organic silts and inorganic sediments, which occur in a regular manner in each of the cores. These changes reflect the changing water balance of the lake and the nature of the material eroded from the watershed. Their significance is discussed in subsequent sections.

The stratigraphy of the master core, F1, is shown on the right side of Figure 3. The core consists of eight units. At its base, overlying the coarse sand/gravelly till (unit I), is a thin deposit (3.5 cm) of grayish brown (Munsell 10 YR 5/2) silts (unit III), enriched with fragments of partly decomposed organic

matter. Above this is a substantial accumulation of peaty material (19.5 cm) (unit IV) with wood fragments. Within the upper third of the unit is a discontinuous layer of Mazama tephra (unit V), a yellow (10 YR 7/6), fine textured deposit with a maximum thickness of 2.0 cm. The Mazama, in contrast to the Bridge River tephra, is not continuous throughout the lake but is concentrated in lenses. The peaty material is overlain by dark gray (10 YR 4/1) silts (unit VI) (11 cm) enriched with organic matter which grades upwards into inorganic silts (4 cm) (unit VII). A distinctive deposit (3-4 cm) of Bridge River tephra occurs in the upper 5-15 cm of all cores (unit VIII). In many of the cores, the tephra has two distinct facies: the lower, coarser unweathered shards; the upper, a finer deposit, a product of finer tephra fallout intermixed with watershed sediments, or a second eruption as suggested by Mathewes and Westgate (1980). The fact that these facies are so obvious must be attributed to the proximity of the study area to the source of the tephra, Meager Mountain, approximately 45 km north of the study site. The uppermost lake sediments (8.5 cm) are grayish brown (10 YR 5/2), inorganic lacustrine silts (unit IX), which become less well consolidated near the surface.

The eight distinct stratigraphic units are represented in a regular fashion throughout the lake. A further unit is identified for subsequent analyses through the subdivision of the surface silts into well and less well consolidated horizons (unit X). A tenth unit (unit II), not evident in the master core is a coarse sand/gravel deposit in cores V1 and V2, immediately above the till, both in the vicinity of one of the incoming streams. A thin charcoal layer in cores C1 and H1, approximately 11 cm above the till within the peaty unit, may indicate a fire in the catchment in early postglacial time.

TABLE II
Minerogenic bulk density and organic matter content by stratigraphic unit (n = sample size)

Stratigraphic unit	Minerogenic bulk density (kg m^{-3})				Organic matter (% dry wt)		
	n	\bar{x}	S.D.	C.V.	\bar{x}	S.D.	C.V.
Upper lacustrine silts (unit X)	52	870	120	0.14	7.28	0.39	0.05
Lacustrine silts (unit IX)	54	880	140	0.16	7.10	0.72	0.10
Lacustrine silts/Bridge River tephra (unit VIII)	5	1350	230	0.17	2.02	0.24	0.12
Lacustrine silts/organic matter (unit VII)	42	420	40	0.09	13.92	1.38	0.10
Organic lacustrine silts (unit VI)	52	290	60	0.21	15.65	2.09	0.11
Peaty/Mazama tephra (unit V)	4	730	120	0.16	5.33	0.56	0.10
Peaty sediment (unit IV)	52	220	40	0.18	22.13	1.62	0.07
Lacustrine silts/organic matter (unit III)	52	320	30	0.10	18.65	1.35	0.07

SEDIMENT CHARACTERISTICS

Table II summarises the mean values of minerogenic bulk density and organic matter content by stratigraphic unit. These were determined to compute influx rates of clastic sediment on a standardised basis (see later discussion). The results for the master core, F1, are presented graphically in Figure 3. Some indication of the degree of variability is provided by the coefficient of variation (C.V.). The minerogenic bulk density exhibits a strong negative correlation with organic matter content. To compare the textural characteristics of the sedimentary environments mean size (M_z), sorting (σ_i) and skewness (sk_i) distribution statistics (Folk and Ward, 1957) are given (Table III). Figure 3 illustrates the variation of graphic statistics with depth for the master core F1. The results of X.R.D. are presented in Table IV. These indicate a consistent balance amongst the minerals present (Table IV). Kaolinite and vermiculite have dominated the mineralogy, with minor amounts of mica, chlorite, quartz, amphibole and plagioclase. Information on extractable Fe and Al, indices of the degree of weathering of the deposited sediments (Birkeland *et al.*, 1979; Arduino *et al.*, 1984), are presented for the master core in Figure 3. These results are discussed in the context of palaeoenvironmental reconstructions in subsequent sections.

TEMPORAL VARIABILITY IN SEDIMENT YIELD

The total volume of sediment accumulated in Gallie Pond was determined through the combination of core, probe and survey data. The volumetric data were converted to sediment yield for the Goat Meadows watershed using minerogenic

TABLE III

Summary of particle size characteristics by stratigraphic unit. The second column for each characteristic indicates one standard deviation

Stratigraphic unit	n	M_z (ϕ)	(σ_{mz}) (ϕ)	σ_i (ϕ)	(σ_i) (ϕ)	sk_i	(σsk_i)
Upper Lacustrine silts (units IX & X)	15	5.51	0.52	1.53	0.45	-0.47	0.10
Lacustrine silts/Bridge River tephra (unit VIII)	3	3.56	0.15	1.19	0.25	0.17	0.04
Lacustrine silts/organic matter (units VI & VII)	6	5.80	0.89	1.52	0.43	-0.46	0.15
Peaty/Mazama tephra (unit V)	4	5.41	0.19	1.55	0.40	-0.32	0.33
Peaty sediment (unit IV)	5	4.82	0.37	1.41	0.02	-0.32	0.21
Lacustrine silts/organic matter (unit III)	3	4.67	0.44	1.79	0.72	-0.15	0.32
Till/oxidised sands (units I & II)	6	2.27	1.44	2.24	0.69	0.15	0.33

TABLE IV

Relative abundance of minerals in <2 µm fraction in the stratigraphic units of the master core

Stratigraphic unit	Kaol.	Ver. ¹	Ver. ²	Mica	Chl.	Qtz.	Amph.	Plag.
Lacustrine silts (unit X)	3	3	3	0	0	0	0	0
Lacustrine silts (unit IX)	3	2	3	0	0	2	1	1
Lacustrine silts/Bridge River tephra (unit VIII)	3	3	2	2	0	1	1	2
Lacustrine silts/organic matter (units VII)	3	3	3	2	2	2	0	0
Organic Lacustrine silts (units VI)	4	3	3	2	2	2	0	0
Peaty/Mazama tephra (unit V)	4	3	3	2	2	2	0	0
Peaty sediment (unit IV)	3	3	3	2	2	2	0	0
Lacustrine silts/organic matter (unit III)	3	3	3	2	2	2	2	2
Till (unit I)	4	3	3	3	2	2	1	2

Kaol. = kaolinite; Ver.¹ = vermiculite; Ver.² = poorly weathered vermiculite-mica/vermiculite intergrade; Chl. = chlorite; Qtz. = quartz; Amph. = amphibole; Plag. = plagioclase
4 = dominant; 3 = abundant; 2 = present; 1 = trace; 0 = not present.

bulk density data. These are reported in Table V as erosion rates for the catchment (kg eroded sediment per m² of the catchment). The error bars ($\pm 2\sigma$) around the estimates of erosion rates (column 3, Table V), relate to the variability of the bulk density within each stratigraphic unit. Chronological control is provided by the two tephra layers and two radiocarbon dates. Further errors are associated with these and are incorporated into the final column of Table V.

DISCUSSION

The following discussion integrates the results presented in the previous sections to provide a summary of palaeogeomorphic processes of the Goat Meadows watershed, as recorded in the sediments of Gallie Pond, for each of the dated time periods.

DEGLACIATION TO 6700 YR BP

This period encompasses the time between deglaciation and Mazama tephra deposition. The basal date on the lake

TABLE V

Sediment yield from the Goat Meadows watershed

Stratigraphic unit	Date (¹⁴ C yrs BP)	Sediment yield (kg m ⁻²)	Sediment yield (x 10 ⁻⁴ kg m ⁻² yr ⁻¹)		
			Mean	Min.	Max.
Lacustrine silts (units IX & X)		0.24 \pm 0.06	2.33	1.66	3.00
Lacustrine silts/Bridge River (unit VIII)		0.32 \pm 0.10			
	2400				
Organic lacustrine silts (units VI & VII)		0.35 \pm 0.06	0.89	0.68	1.13
	6340 \pm 150 (I-11471)				
Peaty/lacustrine silts (upper unit IV)		0.12 \pm 0.05	5.28	1.82	43.3
Peaty/Mazama tephra (unit V)		0.07 \pm 0.02			
	6700				
Peaty sediment (unit IV)		0.35 \pm 0.13	1.16	0.60	2.11
Lacustrine silts/organic matter (unit III)		0.09 \pm 0.02			
	10510 \pm 500 (WAT 670)				
Mean			1.47	0.96	2.08

Area of the Goat Meadows watershed is 0.024 km²; Error bars in column 3 \pm 2 standard deviations, taking into account variability in minerogenic bulk density; Min-Max estimates in columns 5 & 6 incorporate \pm 2 standard deviations in the two ¹⁴C dates.

sediments indicates that deglaciation occurred prior to 10,510 \pm 500 yr BP. This is in accordance with other dates of deglaciation in the area (see Clague, 1981; Saunders *et al.*, 1987), though few have been obtained in the alpine-subalpine ecotone. Mazama tephra is dated at 6700 yr BP (Porter, 1980).

Three stratigraphic units overlying the till were laid down in this period: coarse sands (unit II); lacustrine organic-rich silts (unit III), and fibrous peaty material (unit IV). These reflect a transition from deglaciation, formation of a shallow lake during the early postglacial, and a subsequent fall in water level and the development of a peaty deposit during the early part of the Holocene. The organic deposits, formed prior to 6340 yr BP, correspond to the period of maximum temperatures and minimum precipitation recognised in lowland sites as the "xerothemic interval" by Mathewes and Heusser (1981). Evidence for paraglacial sedimentation comes from the lowest

sands and silts (units II and III) below the peaty deposit, which show a strong correspondence of mineralogy with the till (Table IV) and are coarser than the overlying material (Table III). In the watershed this episode was probably completed by ca. 10,000 BP, but a reliable date is needed.

The textural characteristics of the clastic sediment deposited in the silt and peaty horizons (Table III) indicates the accumulation of progressively finer, increasingly well sorted and more negatively skewed sediments. This gradation suggests an increase in the relative importance of the fine silt fraction, which may possibly be attributed to either an increased input from weathering, substantiated in part by soil profile texture and mineralogy data, or an increase in the aeolian input of sediment. However, the hillslope soil profiles indicate that Mazama tephra is located near the base and is overlain by substantial (0.3 m) accumulations of aeolian material. This suggests that most aeolian activity within the catchment occurred after 6700 yr BP.

During this period episodic high-frequency events in the Hummingbird subcatchment were responsible for introducing deposits of coarse sand (unit II) into the eastern part of the lake, evident in cores VI and V2.

The mineralogy of the lake deposits is very similar to that of the underlying till (see Table IV), reflecting the input of sediment from sparsely vegetated areas near both the pond and the tributary streams. During the xerothermic interval, when the water level fell, the dominant source of sediment was probably the till shelf. However, there is an abundance of amphibole and plagioclase in the till not evident in the peaty horizon, indicating that these minerals may have been amongst the first to have weathered during that warmer period.

The erosion of clastic sediment for this early period averaged 1.16×10^{-4} (min 0.60×10^{-4} , max 2.11×10^{-4}) $\text{kg m}^{-2} \text{yr}^{-1}$, a rate lower than the Holocene average. However, the high organic matter content and low bulk density of the sediments yielded a high volumetric influx ($0.01 \text{ m}^3 \text{yr}^{-1}$).

6700 - 6340 YR BP

The period 6700 — 6340 yr BP represents the end of the warm dry conditions of the xerothermic interval. The stratigraphy of the deposits from this period shows a discontinuous layer of Mazama tephra overlain by fibrous peaty material (unit V), with woody fragments indicating a tree line higher than present. Organic matter in the sediments is high and primarily derived *in situ*, as indicated by the fibrous organic matrix of the deposit.

The Mazama tephra is fine textured and well sorted (Table III) a consequence of the distance from its source in southern Oregon. The peaty horizon in which it is incorporated is finer (mean size 5.41 ϕ) than those of peaty horizons below (4.82 ϕ), although less well sorted (Table III), a consequence of the inter-mixing of tephra with watershed sediments.

The mineralogy of the sediments shows a strong till imprint (see Table IV), indicating a similar source area to that evident in the early postglacial. A slight increase in extractable iron and aluminum content of the sediments (Fig. 3) indicates that

the hillslopes were contributing, and increasingly well weathered material was accumulating.

Influx rates for this period, in terms of both volume and mass of clastic sediment accumulated, are the highest recorded over the postglacial period (Table V). However, at this time the inflowing streams were flowing infrequently, if at all. A possible explanation for the high inflow rates is the large input of Mazama tephra by direct air-fall. However, when the volume of Mazama tephra is excluded from influx calculations, rates remain above average for the Holocene. More probable explanations for this include: 1) shorter duration of snow cover and therefore a longer period for the operation of erosional processes; 2) the exposure of the till shelf by a fall in water level; 3) increased aeolian activity within the catchment; 4) a fire in the catchment during this interval as indicated by the charcoal in cores C1 and H1; or, 5) the relatively high trap efficiency of the peaty material, for all size fractions. The latter provides a possible explanation for the poor sorting of the deposits (Table III), but little substantiation is available from the relative trap efficiencies of small ponds and peaty deposits.

6340 to 2400 YR BP

The onset of this period was probably characterised by general cooling and wetter conditions. This is shown in the stratigraphy by accumulation of inorganic clastic sediments (units VI and VII) which represent a rise of the water table and flooding of the site to form a shallow lake. The inorganic matter incorporated in the sediment is primarily allochthonous fragments of woody material derived from decomposing vegetation and dead trees and/or shrubs left in the basin as the tree line fell.

The deposits are the finest textured in the lake record (Mz 5.8 ϕ), indicating significant input of fine silts and coarse clay. The sediments are moderately sorted (1.52 ϕ) and negatively skewed (-0.46). Such skewness values indicate environments with relatively low erosional energy in which the predominant erosional events transported finer material derived from winnowing of terrestrial deposits, with less frequent movement of the coarser fraction. Pedogenesis during the preceding xerothermic interval resulted in greater weathering of the hillslope deposits. An increase in extractable iron and aluminum content of the sediments from this period indicates sediment influx from the hillslopes.

Accumulation of clastic sediments, both in terms of volume and influx of clastic sediments, is the lowest recorded in the postglacial period. Hence, this period is one of limited activity in terms of volume of sediment moved, but marks the onset of the input of dominantly pedogenic weathered sediments.

2400 YR BP TO THE PRESENT

The sediments accumulating in the period 2400 — 0 yr BP are the silts with the least organic matter (units IX and X), reflecting the onset of the coolest Neoglacial conditions. At the base of these deposits is Bridge River tephra consisting of coarse shards of well sorted volcanic glass.

The silts of the unit are fine textured, (Mz 5.51 ϕ), moderately sorted and negatively skewed. The mineralogy and extractable iron and aluminum content all indicate a pedogenic source for the sediment, probably surface horizons of the Brunisols and Regosols within the catchment.

The period is characterised by an increase in clastic sediment erosion from the catchment to $2.33 \times 10^{-4} \pm 0.67 \times 10^{-4} \text{ kg m}^{-2} \text{ yr}^{-1}$. This above average rate for the Holocene appears to be related to the wetter conditions and the relative importance of channel and slope wash processes.

SUMMARY

Interpretation of the characteristics of the lake sediments of Gallie Pond indicates relative stability and quiescence in terms of Holocene geomorphic activity in the Goat Meadows watershed. However, a number of events with regional significance can be recognised.

The paraglacial period (Church and Ryder, 1972), may have been completed early in this alpine/subalpine catchment. It is probable that the higher energy conditions at the site, recorded as oxidised sands and coarser less well sorted lacustrine silts at the base of the core, resulted in the redistribution of glacial sediment and after that conditions of greater stability and reduced levels of sediment flux prevailed.

The transition from xerothermic to cooler Neoglacial conditions varied regionally in the Pacific Northwest, from 7000 to 6000 yr BP in coastal British Columbia and adjacent Washington State, to 4000 to 3000 yr BP east of the Coast and Cascade Mountains (Ryder and Thompson, 1986; Osborn and Luckman, 1987). The results of this study support the earlier date for the Coast Mountains, as evidenced by the stratigraphic change from peaty material to organic-rich lacustrine silts ca. 6300 yr BP, indicating the onset of cooler, wetter conditions. The progressive decrease in organic matter in the lake sediments representing the last 6000 years, an index of net organic productivity in the catchment, lends support to the argument of progressive cooling of the three Neoglacial intervals. However, given the dating control and subsampling of this study it is not possible to resolve each Neoglacial in the lake sediment record.

CONCLUSION

This study indicates that pond sediments offer insight into palaeogeomorphic change, through determinations of sedimentation rates, mechanisms of sediment transfer, sediment sources or organic productivity. Despite the small size of the study watershed, the details of the Holocene record are generally consistent with the results from larger scale systems, which in some cases may be many thousand times larger, and where regional changes in past climate are inferred through the filtering effect of large basin dynamics.

The highly conservative sedimentary response indicates that the Goat Meadows watershed remained a relatively low energy erosional system throughout the Holocene epoch. However, the characteristics investigated in this study provide insight into changes in the water balance of the lake, gross

changes in sediment sources, organic productivity and sedimentation rates, all of which are consistent with regional climate change.

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